

Enabling Interactive C++ in Clang

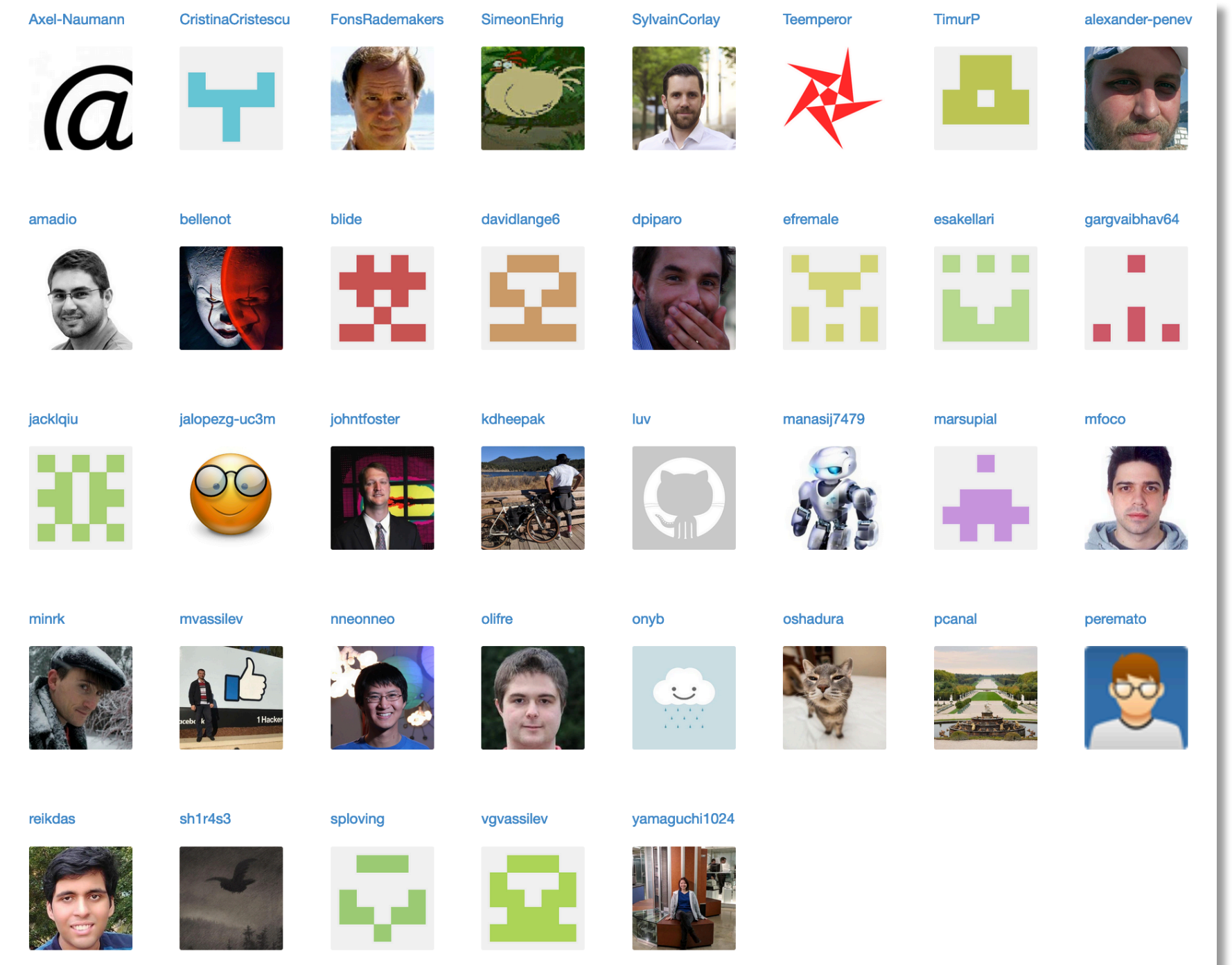
Vassil Vassilev, Princeton University
compiler-research.org

Outline

- Introduction
 - Key insights of Interactive C++
 - Interpreting C++. Tools and technology
- Applications of interactive C++
 - C++ in Jupyter notebooks; Interactive CUDA C++; Automatic language bindings; Eval-style programming
- Compiler As A Service
 - Crossing compile-time/runtime boundaries; Extensions; Automatic differentiation
- Evolving the technology towards Clang mainline via Clang-Repl
 - Showcase incremental compilation in Clang; Demonstrate template instantiation in C and Python
- Summary

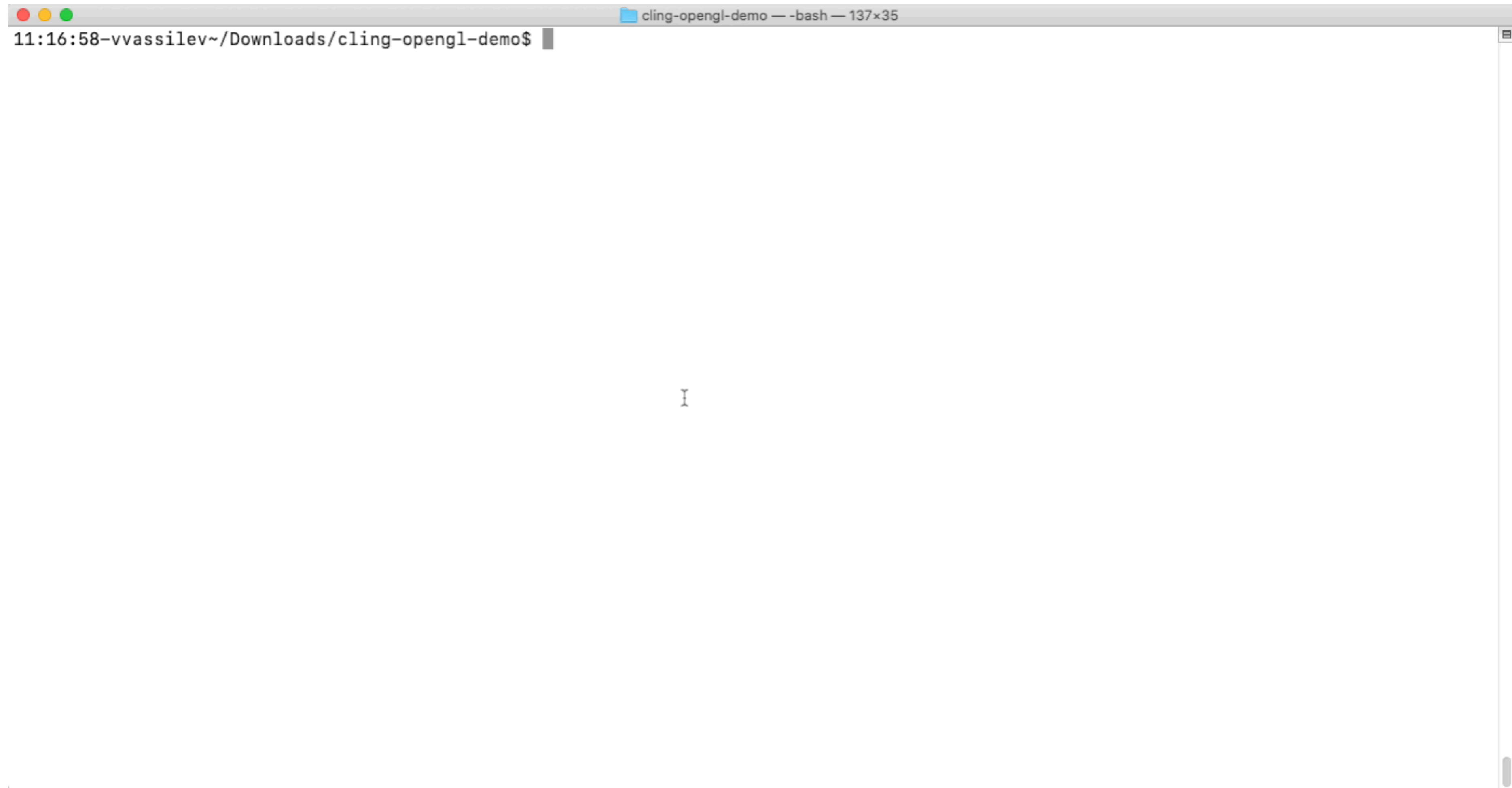
Acknowledgement & Disclaimer

- This talk includes technologies developed by various individuals and organizations in the area of interpretative C++ since 1998
- This talk is about work conducted by me but also the work of dozens colleagues and contributors from science and industry. In the slides I have tried to mention individuals and organizations where possible.
- Any characterizations, mischaracterizations, emphasis or errors are solely mine and do not necessarily represent the views of other individuals or organizations.



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Interactive C++



Video Credits: A. Penev

The invisible compile-run cycle aids interactive use and offers a different programming experience while enhancing productivity. It becomes trivial to orient a shape, choose size and color or compare to previous settings

Interactive C++. Key Insights

- Incremental Compilation
- Handling errors
 - Syntactic
 - Semantic
- Execution of statements
- Displaying execution results
- Entity redefinition

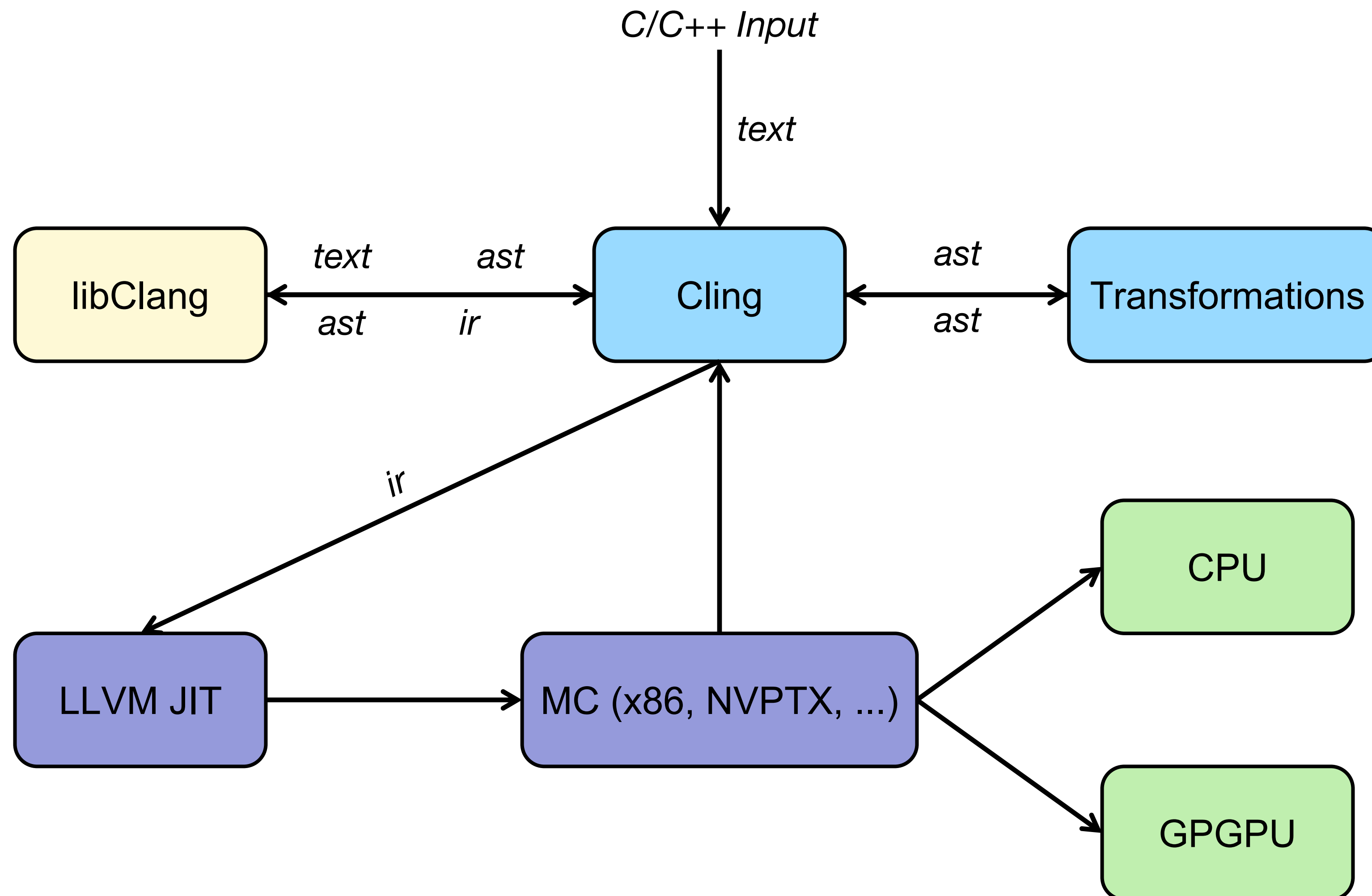
```
[cling] #include <vector>
[cling] std::vector<int> v = {1,2,3,4,5};
```

```
[cling] std.sort(v.begin(), v.end());
input_line_1:1:1: error: unexpected namespace
name 'std': expected expression
std.sort(v.begin(), v.end());
^
```

```
[cling] std::sort(v.begin(), v.end());
[cling] v // No semicolon
(std::vector<int> &) { 1, 2, 3, 4, 5 }
```

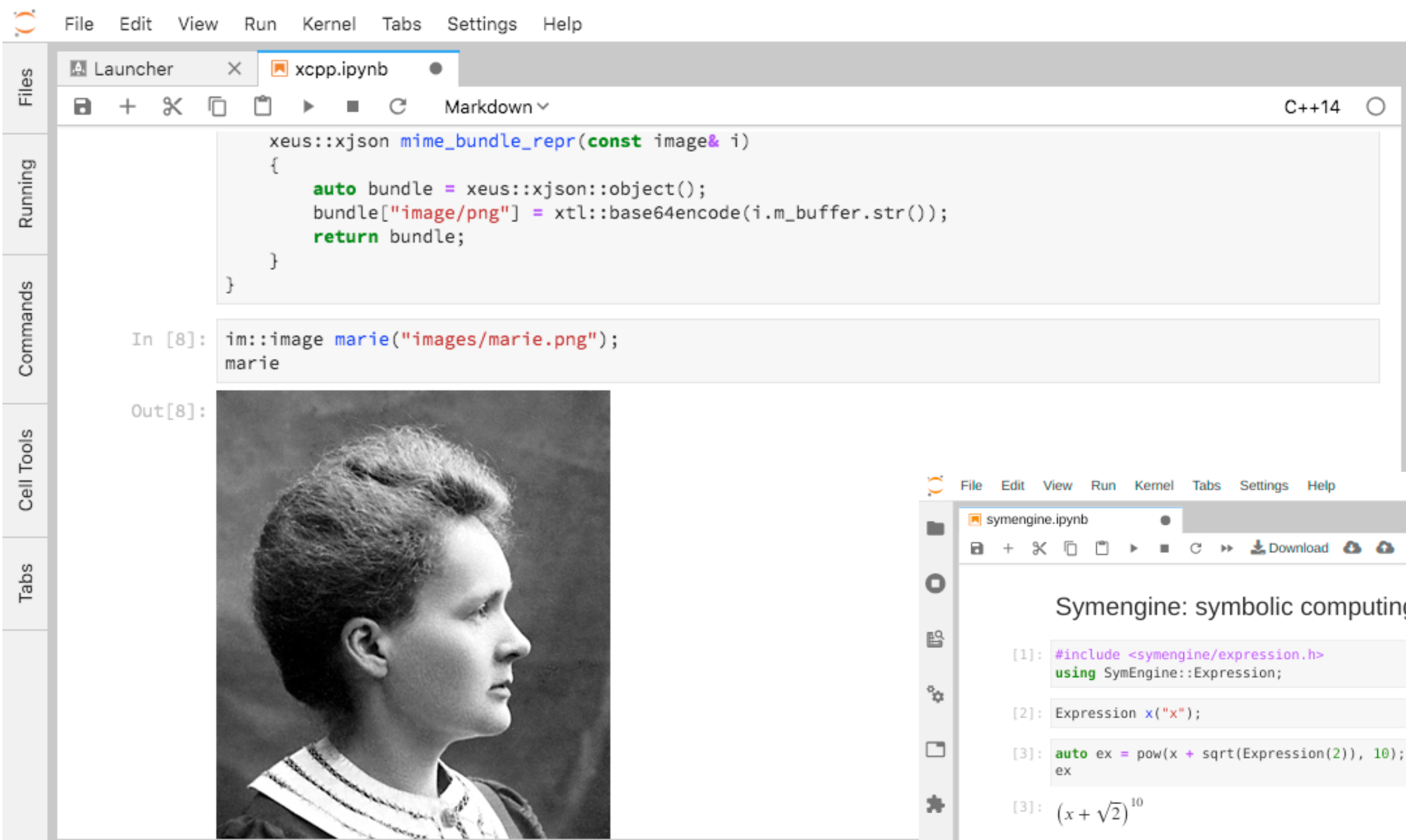
```
[cling] std::string v = "Hello World"
(std::string &) "Hello World"
```

Interpreting C++. Cling




Applications of Interactive C++

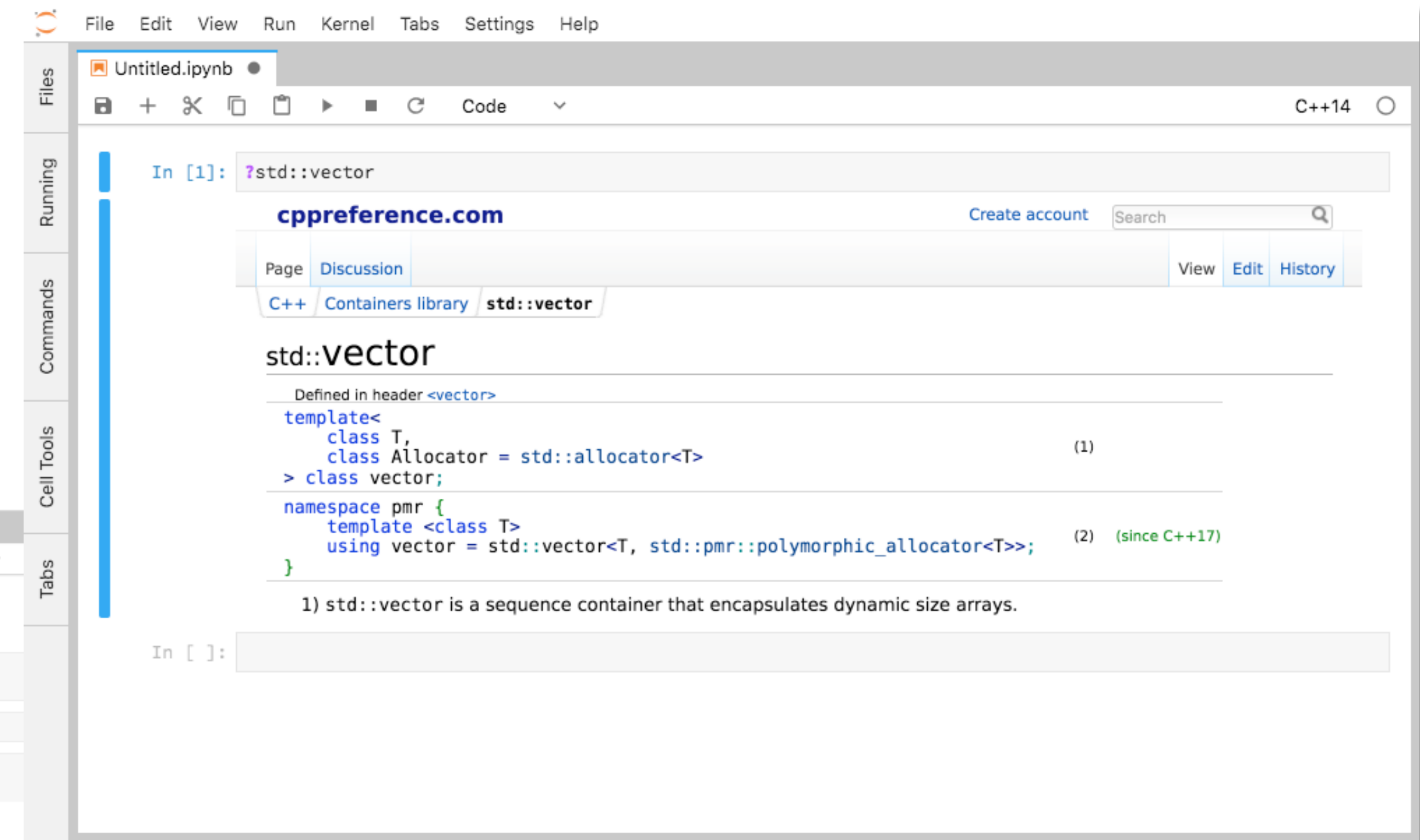
Xeus-Cling. C++ in Notebooks



The screenshot shows a Jupyter notebook interface with the following content:

```
File Edit View Run Kernel Tabs Settings Help
xcpp.ipynb
Markdown C++14
xeus::xjson mime_bundle_repr(const image& i)
{
    auto bundle = xeus::xjson::object();
    bundle["image/png"] = xtl::base64encode(i.m_buffer.str());
    return bundle;
}
In [8]: im::image marie("images/marie.png");
marie
Out[8]: 
```

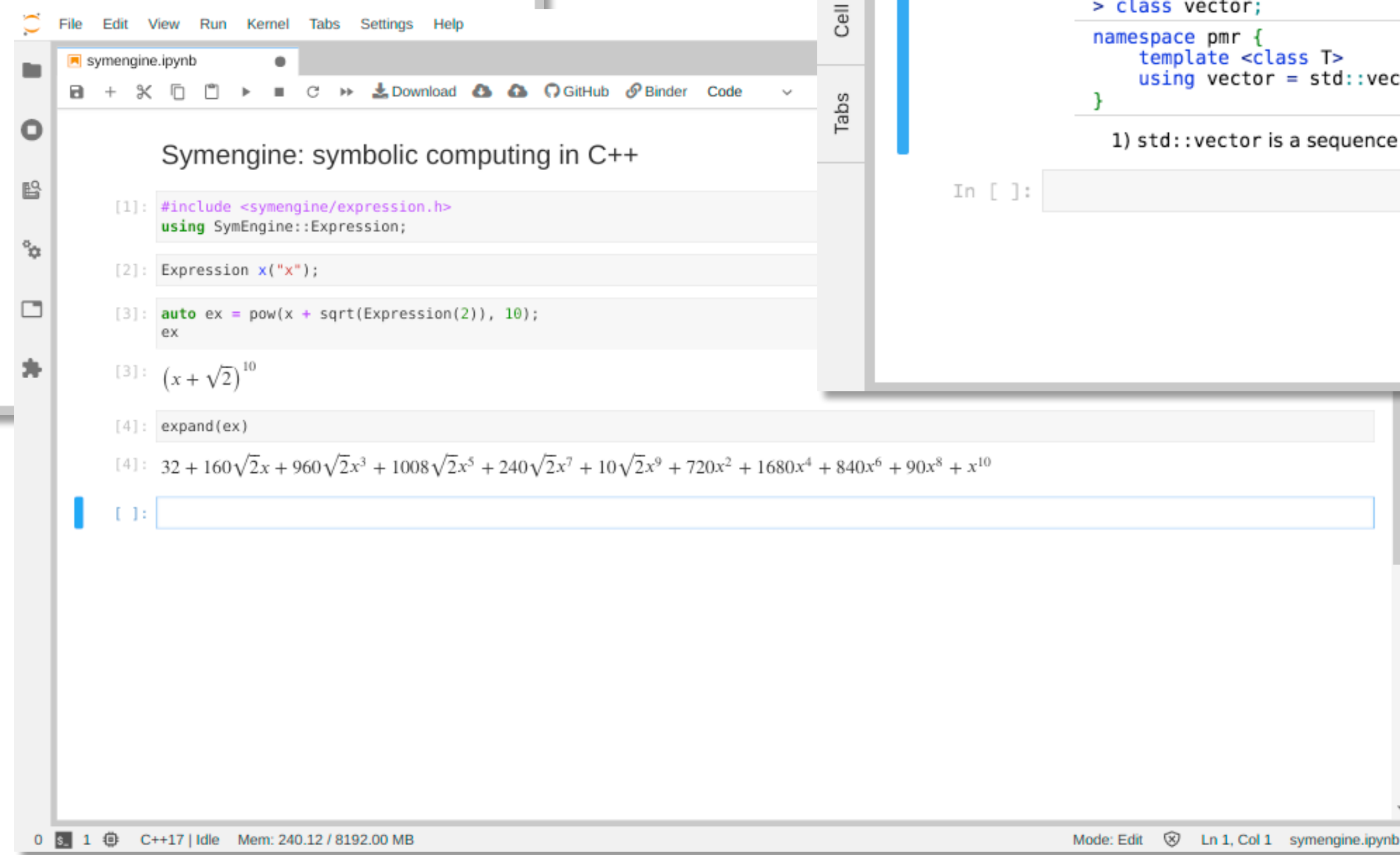
Visualization of user-defined images



The screenshot shows a Jupyter notebook interface with the following content:

```
File Edit View Run Kernel Tabs Settings Help
Untitled.ipynb
Code C++14
In [1]: ?std::vector
cppreference.com
Page Discussion Create account Search
C++ Containers library std::vector
std::vector
Defined in header <vector>
template<
    class T,
    class Allocator = std::allocator<T>
> class vector; (1)
namespace pmr {
    template <class T>
        using vector = std::vector<T, std::pmr::polymorphic_allocator<T>>; (2) (since C++17)
}
1) std::vector is a sequence container that encapsulates dynamic size arrays.
In [ ]:
```

Direct access to documentation

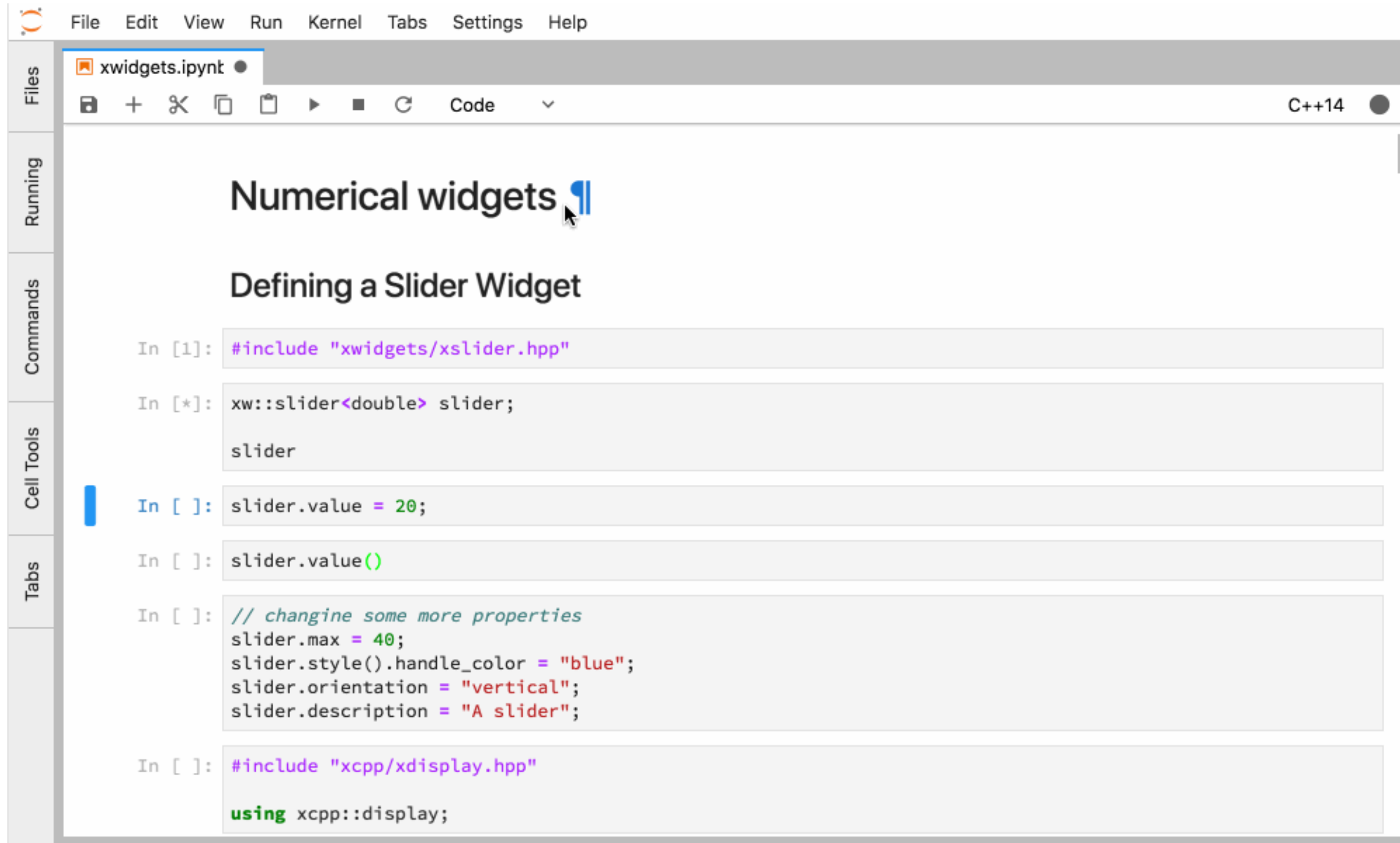


The screenshot shows a Jupyter notebook interface with the following content:

```
File Edit View Run Kernel Tabs Settings Help
symengine.ipynb
Download GitHub Binder Code
Symengine: symbolic computing in C++
[1]: #include <symengine/expression.h>
using SymEngine::Expression;
[2]: Expression x("x");
[3]: auto ex = pow(x + sqrt(Expression(2)), 10);
ex
[3]: (x + sqrt(2))^10
[4]: expand(ex)
[4]: 32 + 160sqrt(2)x + 960sqrt(2)x^3 + 1008sqrt(2)x^5 + 240sqrt(2)x^7 + 10sqrt(2)x^9 + 720x^2 + 1680x^4 + 840x^6 + 90x^8 + x^10
[ ]:
```

Rich mime type rendering in Jupyter

Xeus-Cling. C++ in Notebooks



The screenshot shows a Jupyter notebook interface with a menu bar (File, Edit, View, Run, Kernel, Tabs, Settings, Help) and a toolbar. The active file is 'xwidgets.ipynt'. The notebook content includes a title 'Numerical widgets' and a sub-section 'Defining a Slider Widget'. The code cells contain the following C++ code:

```
In [1]: #include "xwidgets/xslider.hpp"

In [*]: xw::slider<double> slider;

slider

In [ ]: slider.value = 20;

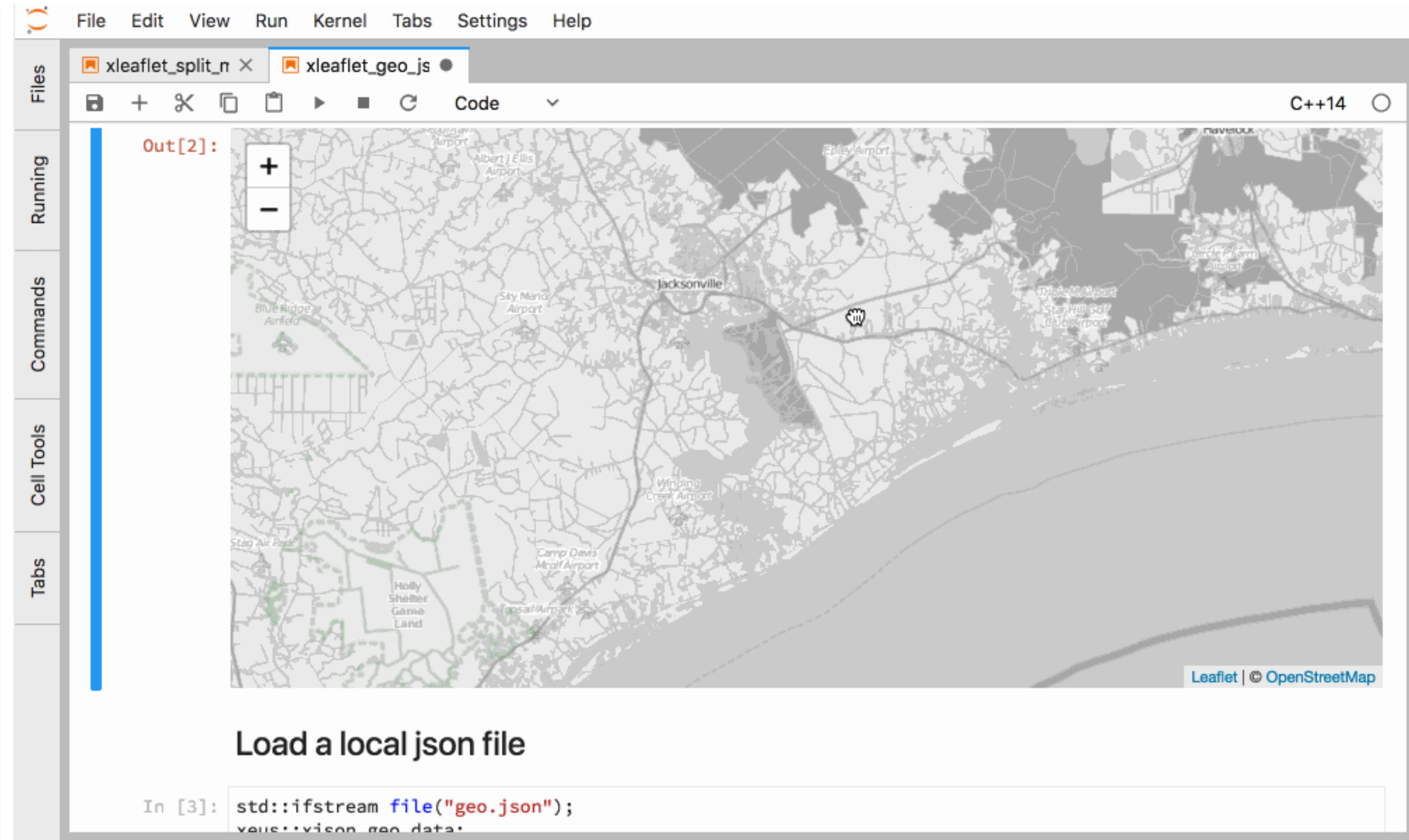
In [ ]: slider.value()

In [ ]: // change some more properties
slider.max = 40;
slider.style().handle_color = "blue";
slider.orientation = "vertical";
slider.description = "A slider";

In [ ]: #include "xcpp/xdisplay.hpp"

using xcpp::display;
```

Xwidgets – User-defined controls



The screenshot shows a Jupyter notebook interface with a menu bar (File, Edit, View, Run, Kernel, Tabs, Settings, Help) and a toolbar. The active file is 'xleaflet_geo.js'. The notebook content includes a title 'Load a local json file' and a sub-section 'Interactive Geo Information System'. The code cell contains the following C++ code:

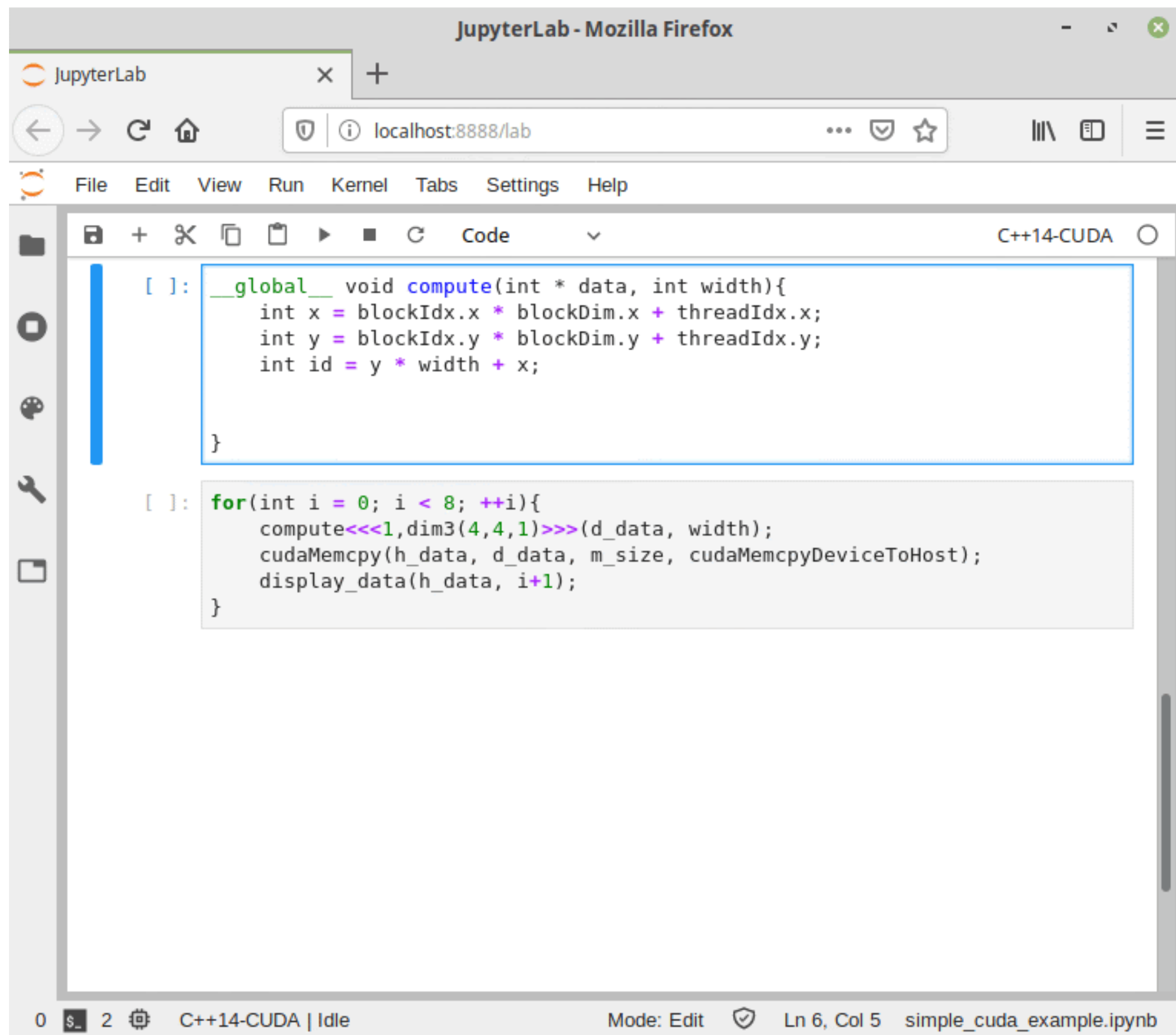
```
In [3]: std::ifstream file("geo.json");
xleaflet::xleaflet_geo data;
```

The output of the code cell is a map of Jacksonville, Florida, with a vertical slider control on the left side. The map is titled 'Out[2]:' and shows a street view of the city. The slider control has a plus sign and a minus sign, and is currently set to a value of 20. The map is titled 'Leaflet | © OpenStreetMap'.

Xleaflet – Interactive Geo Information System

S. Corlay, Quantstack, [Deep dive into the Xeus-based Cling kernel for Jupyter](https://compiler-research.org/deep-dive-into-the-xeus-based-cling-kernel-for-jupyter/), May 2021, compiler-research.org

Interactive CUDA C++



JupyterLab - Mozilla Firefox

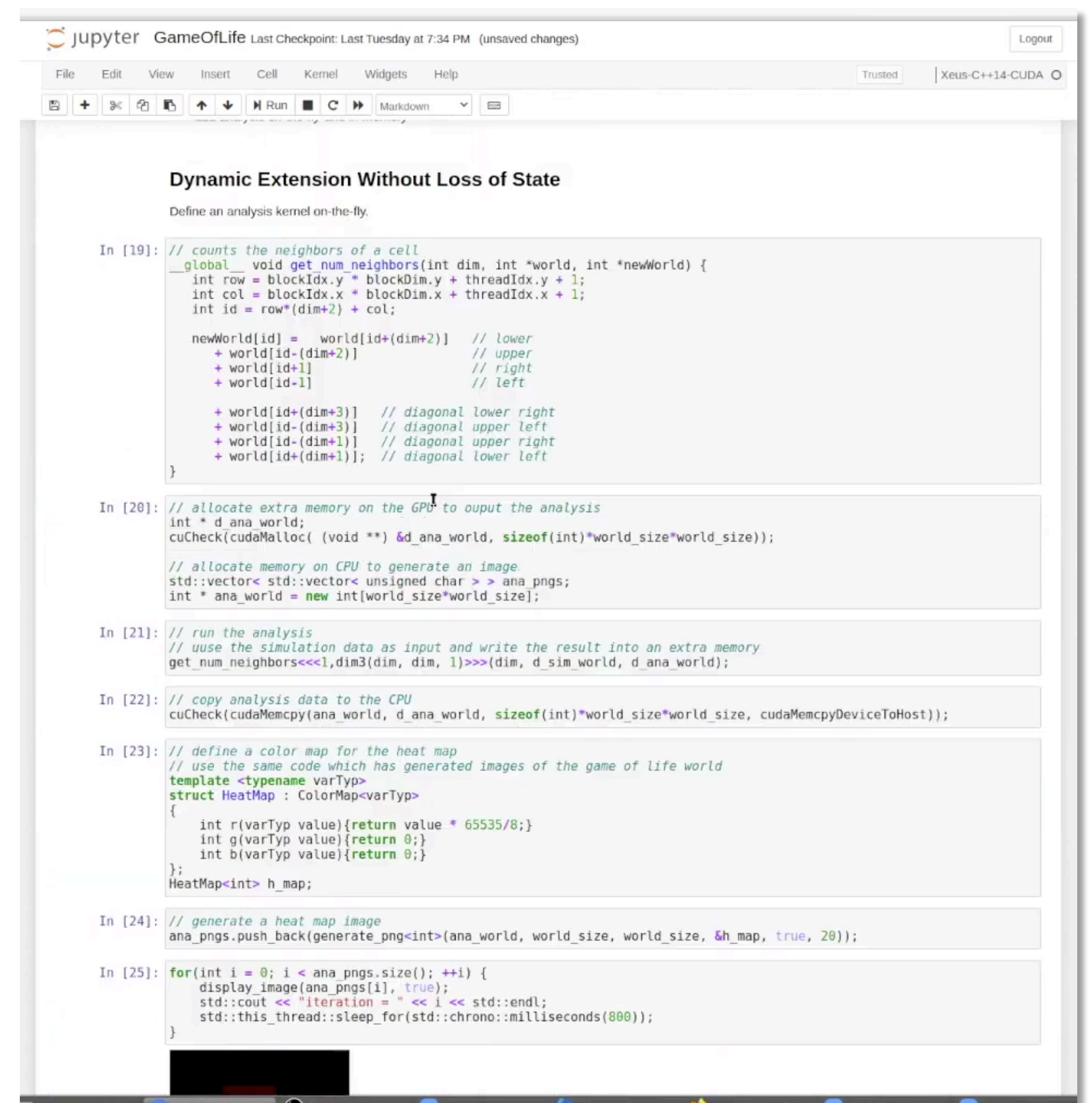
localhost:8888/lab

File Edit View Run Kernel Tabs Settings Help

```
[ ]: __global__ void compute(int * data, int width){
    int x = blockIdx.x * blockDim.x + threadIdx.x;
    int y = blockIdx.y * blockDim.y + threadIdx.y;
    int id = y * width + x;
}
```

```
[ ]: for(int i = 0; i < 8; ++i){
    compute<<<1,dim3(4,4,1)>>>(d_data, width);
    cudaMemcpy(h_data, d_data, m_size, cudaMemcpyDeviceToHost);
    display_data(h_data, i+1);
}
```

0 2 C++14-CUDA | Idle Mode: Edit Ln 6, Col 5 simple_cuda_example.ipynb



jupyter GameOfLife Last Checkpoint: Last Tuesday at 7:34 PM (unsaved changes)

File Edit View Insert Cell Kernel Widgets Help Trusted Xeus-C++14-CUDA

Dynamic Extension Without Loss of State

Define an analysis kernel on-the-fly.

```
In [19]: // counts the neighbors of a cell
__global__ void get_num_neighbors(int dim, int *world, int *newWorld) {
    int row = blockIdx.y * blockDim.y + threadIdx.y + 1;
    int col = blockIdx.x * blockDim.x + threadIdx.x + 1;
    int id = row*(dim+2) + col;

    newWorld[id] = world[id+(dim+2)] // lower
                + world[id-(dim+2)] // upper
                + world[id+1] // right
                + world[id-1] // left

                + world[id+(dim+3)] // diagonal lower right
                + world[id-(dim+3)] // diagonal upper left
                + world[id-(dim+1)] // diagonal upper right
                + world[id+(dim+1)]; // diagonal lower left
}
```

```
In [20]: // allocate extra memory on the GPU to output the analysis
int * d_ana_world;
cuCheck(cudaMalloc( (void **) &d_ana_world, sizeof(int)*world_size*world_size));

// allocate memory on CPU to generate an image
std::vector< std::vector< unsigned char > > ana_pngs;
int * ana_world = new int[world_size*world_size];
```

```
In [21]: // run the analysis
// use the simulation data as input and write the result into an extra memory
get_num_neighbors<<<1,dim3(dim, dim, 1)>>>(dim, d_sim_world, d_ana_world);
```

```
In [22]: // copy analysis data to the CPU
cuCheck(cudaMemcpy(ana_world, d_ana_world, sizeof(int)*world_size*world_size, cudaMemcpyDeviceToHost));
```

```
In [23]: // define a color map for the heat map
// use the same code which has generated images of the game of life world
template <typename varTyp>
struct HeatMap : ColorMap<varTyp>
{
    int r(varTyp value){return value * 65535/8;}
    int g(varTyp value){return 0;}
    int b(varTyp value){return 0;}
};
HeatMap<int> h_map;
```

```
In [24]: // generate a heat map image
ana_pngs.push_back(generate_png<int>(ana_world, world_size, world_size, &h_map, true, 20));
```

```
In [25]: for(int i = 0; i < ana_pngs.size(); ++i) {
    display_image(ana_pngs[i], true);
    std::cout << "iteration = " << i << std::endl;
    std::this_thread::sleep_for(std::chrono::milliseconds(800));
}
```

S. Ehrig, HZDR, [Cling's CUDA Backend: Interactive GPU development with CUDA C++](https://compiler-research.org), Mar 2021, compiler-research.org

Automatic Language Bindings

cppyy: Yet another Python – C++ binder?!

- Yes, but it has its niche: *bindings are runtime*
 - Python is all runtime, so runtime is more natural
 - C++-side runtime-ness is provided by Cling
- Very complete feature-set (not just “C with classes”)
- Good performance on CPython; great with PyPy*

pip: <https://pypi.org/project/cppyy/>
 conda: <https://anaconda.org/conda-forge/cppyy>
 git: <https://github.com/wlav/cppyy>
 docs: <https://cppyy.readthedocs.io/en/latest/>

For HEP users: *cppyy* in *ROOT* is an old fork. It won't run all the examples here, doesn't work with PyPy, and has worse performance.

(*) PyPy support lags CPython

[1]

sil-cling: Interface with cppyy

- binds with cppyy through the direct inclusion of the latter's C header using dpp

```
1 //cling.dpp
2
3 #include "capi.h" // cppyy's C header
4
5 // D code ↓
6 import std.string : fromStringz, toStringz;
7
8 string resolveName(string cppItemName)
9 {
10     import core.stdc.stdlib : free;
11     // Calling cppyy_resolve_name ↓
12     char* chars = cppyy_resolve_name(cppItemName.toStringz);
13     string result = chars.fromStringz.idup;
14     free (chars);
15     return result;
16 }
```

```
→ ~ dub run dpp -- cling.dpp --keep-d-files -c
```

[2]

How does it work? - Runtime

```
julia> cxx"""
    struct nontrivial { ~nontrivial() { $(println("I got deleted")); }; }
    """
true

julia> a = icxx"nontrivial{};"
(struct nontrivial) {
}

julia> a = nothing;
Last reference dropped here

julia> # Some time later

julia> GC.gc()
Julia GC deletes object => C++ destructor called
I got deleted
```

Nesting works also at global scope

[3]

[1] W. Lavrijsen, LBL, [cppyy](https://compiler-research.org), Sep 2021, compiler-research.org

[2] A. Militaru, Symmetry Investments, [Calling C++ libraries from a D-written DSL: A cling/cppyy-based approach](https://compiler-research.org), Feb 2021, compiler-research.org

[3] K. Fischer, Julia Computing, [A brief history of Cxx.jl](https://compiler-research.org), Aug 2021, compiler-research.org

Eval-Style Programming

```
[cling]$ #include <cling/Interpreter/Value.h>
[cling]$ #include <cling/Interpreter/Interpreter.h>
[cling]$ int i = 1;
[cling]$ cling::Value V;
[cling]$ gCling->evaluate("++i", V);
[cling]$ i
(int) 2
[cling]$ V
(cling::Value &) boxes [(int) 2]
[cling]$ ++i
(int) 3
[cling]$ V
(cling::Value &) boxes [(int) 2]
```

Eval-style programming enables Cling to be embedded in frameworks.

Key Insights

- Cling is not just a Repl, it is an embeddable and extensible execution system for efficient incremental execution of C++
- Cling is used in several high-performance systems to provide reflection and introspection information
- Cling can produce efficient code for performance-critical tasks where hot-spot regions can be annotated with specific optimization levels
- Cling allows us to decide how much we want to compile statically and how much to defer for the target platform

Compiler As A Service

Compiler As A Service (CaaS)

Cling can be used on-demand, as a service, to compile, modify, describe or extend C++.

CaaS. Crossing Boundaries

```
/// Call an interpreted function using its symbol address.
void callInterpretedFn(cling::Interpreter& interp) {
    // Declare a function to the interpreter. Make it extern "C"
    // to remove mangling from the game.
    interp.declare("#pragma cling optimize(1)"
        extern \"C\" int cube(int x) { return x * x * x; }");
    void* addr = interp.getAddressOfGlobal("cube");
    using func_t = int(int);
    func_t* pFunc = cling::utils::VoidToFunctionPtr<func_t*>(addr);
    std::cout << "7 * 7 * 7 = " << pFunc(7) << '\n';
}
```

```
// caas-demo.cpp
// g++ ... caas-demo.cpp; ./caas-demo
int main(int argc, const char* const* argv) {
    cling::Interpreter interp(argc, argv, LLVM_DIR);

    callInterpretedFn(interp);
    return 0;
}
```

```
[vassilev@vv-nuc ~/.../builddir $ ./caas-demo
7 * 7 * 7 = 343
vassilev@vv-nuc ~/.../builddir $
```


CaaS. Extensions

```
int main(int argc, const char* const* argv) {  
    std::vector<const char*> argvExt(argv, argv+argc);  
    argvExt.push_back("-fplugin=etc/clang/plugins/lib/clad.so");  
    cling::Interpreter interp(argvExt.size(), &argvExt[0], LLVMDIR);  
    gimme_pow2dx(interp);  
    return 0;  
}
```

CaaS. Clad Extension for AutoDiff

```
#include <...>
// Derivatives as a service.
void gimme_pow2dx(cling::Interpreter &interp) {
    // Definitions of declarations injected also into cling.
    interp.declare("double pow2(double x) { return x*x; }");
    interp.declare("#include <clad/Differentiator/Differentiator.h>");
    interp.declare("#pragma cling optimize(2)");
    interp.declare("auto dfdx = clad::differentiate(pow2, 0);");

    cling::Value res; // Will hold the evaluation result.
    interp.process("dfdx.getFunctionPtr();", &res);

    using func_t = double(double);
    func_t* pFunc = res.getAs<func_t*>();
    printf("dfdx at 1 = %f\n", pFunc(1));

    interp.process("dfdx.getCode();", &res);
    printf("dfdx code: %s\n %s\n", res.getAs<const char*>());
}
```

```
vvassilev@vv-nuc ~/.../builddir $ ./caas-demo
dfdx at 1 = 2.000000
dfdx code: double pow2_darg0(double x) {
    double _d_x = 1;
    return _d_x * x + x * _d_x;
}
vvassilev@vv-nuc ~/.../builddir $
```

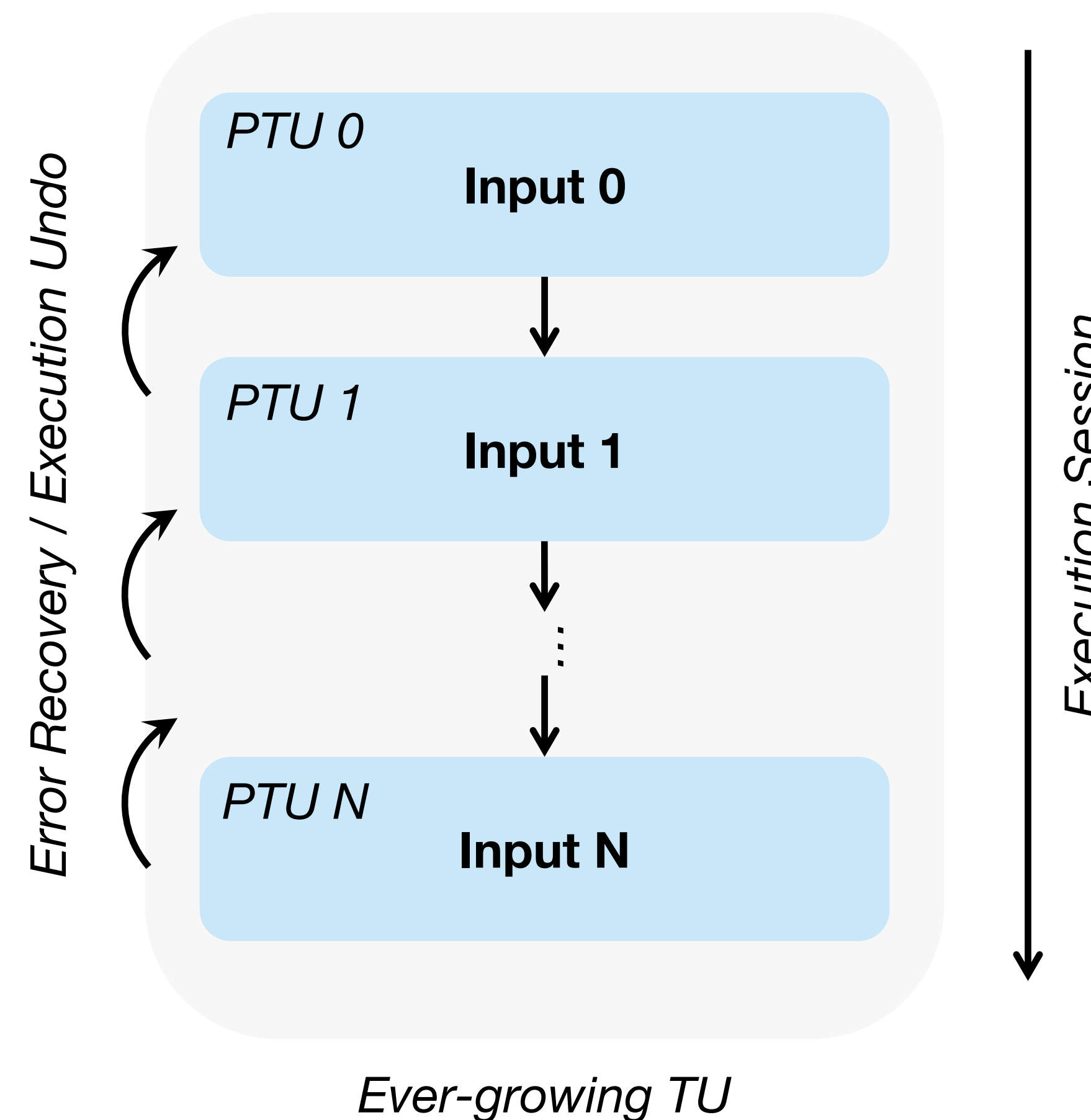
Evolving Cling Into CaaS and Clang-Repl in LLVM Mainline

Evolving Cling Into CaaS and Clang-Repl

- Generalize Cling in a tool available in LLVM mainline (clang/tools/clang-repl)
- Consolidate various incremental compilation APIs in Clang (clang/lib/Interpreter)
- Advance the incremental compilation support in Clang
- libclangInterpreter and clang-repl are available in LLVM13

Ever-growing TU in Clang

- We can split the translation unit into a sequence of partial translation units (PTU)
- Processing a PTU might extend an earlier PTU (template instantiation)
- Each PTU can have its own allocator



Incremental Compilation in Clang

```
#include "clang/Interpreter/Interpreter.h"
// ...
int main() {
    std::vector<const char*> Args;
    auto CI = clang::IncrementalCompilerBuilder::create(Args);
    auto Interp = clang::Interpreter::create(std::move(CI));
    auto PTU = Interp->Parse("extern \"C\" int printf(const char*,...);");
    Interp->ParseAndExecute("auto r = printf(\"Hello interpreted world\");");
    // prints 'Hello interpreted world'
}
```


Instantiating a C++ template in C

```
// gcc ... template_instantiate_demo.C
#include "InterpreterUtils.h" // libInterOp.so

int main(int argc, char **argv) {
    Clang_Parse("void* operator new(__SIZE_TYPE__,
void* __p);"
        "extern \"C\" int printf(const char*,...);"
        "class A {};"
        "\n#include <typeinfo> \n"
        "struct B {"
            "    template<typename T>"
            "    void callme(T) {"
            "        printf(\" Instantiated with [%s] \\n \",
typeid(T).name());"
            "    }"
            "};");
    const char * InstArgs = "A*";
    Decl_t T = Clang_LookupName("A");
    Decl_t TemplatedClass = Clang_LookupName("B");
```

```
// ...
// Instantiate B::callme with the given types
Decl_t Inst
    = Clang_InstantiateTemplate(TemplatedClass,
"callme", InstArgs);

// Get the symbol to call
typedef void (*fn_def)(void*);
fn_def callme_fn_ptr
    = (fn_def) Clang_GetFunctionAddress(Inst);

// Create object of type T
void* NewT = Clang_CreateObject(T);

callme_fn_ptr(NewT);

return 0;
}
```

```
vvassilev@vv-nuc ~/.../cpptemplate $ LD_LIBRARY_PATH="." ./template_instantiate_demo.out
Instantiated with [P1A]
vvassilev@vv-nuc ~/.../cpptemplate $ LD_LIBRARY_PATH="." ./template_instantiate_demo.out "class MyClass1{};" "MyClass1" "MyClass1*"
Instantiated with [P8MyClass1]
vvassilev@vv-nuc ~/.../cpptemplate $ █
```

Instantiating a C++ template in Python

```
# template_instantiate_demo.py
import ctypes

libInterop = ctypes.CDLL("./libInterOp.so")
# tell ctypes which function to call and what are the
expected in/out types.
_cpp_compile = libInterop.Clang_Parse
_cpp_compile.argtypes = [ctypes.c_char_p]

def cpp_compile(arg):
    return _cpp_compile(arg.encode("ascii"))

# define some classes to play with
cpp_compile(r"""
void* operator new(__SIZE_TYPE__, void* __p);
extern "C" int printf(const char*,...);
class A {};
class B {
public:
    template<typename T, typename S>
    void callme(T, S) { printf(" callme in B! \n"); }
};
""")
...

```

```
# initialize our C++ interoperability layer wrapper
gIL = InterOpLayerWrapper()

if __name__ == '__main__':
    # create a couple of types to play with
    A = type('A', (), {
        'handle' : gIL.get_scope('A'),
        '__new__' : cpp_allocate
    })
    h = gIL.get_scope('B')
    B = type('B', (A,), {
        'handle' : h,
        '__new__' : cpp_allocate,
        'callme' : TemplateWrapper(h, 'callme')
    })

    # call templates
    a = A()
    b = B()

    # explicit template instantiation
    b.callme['A, int'](a, 42)

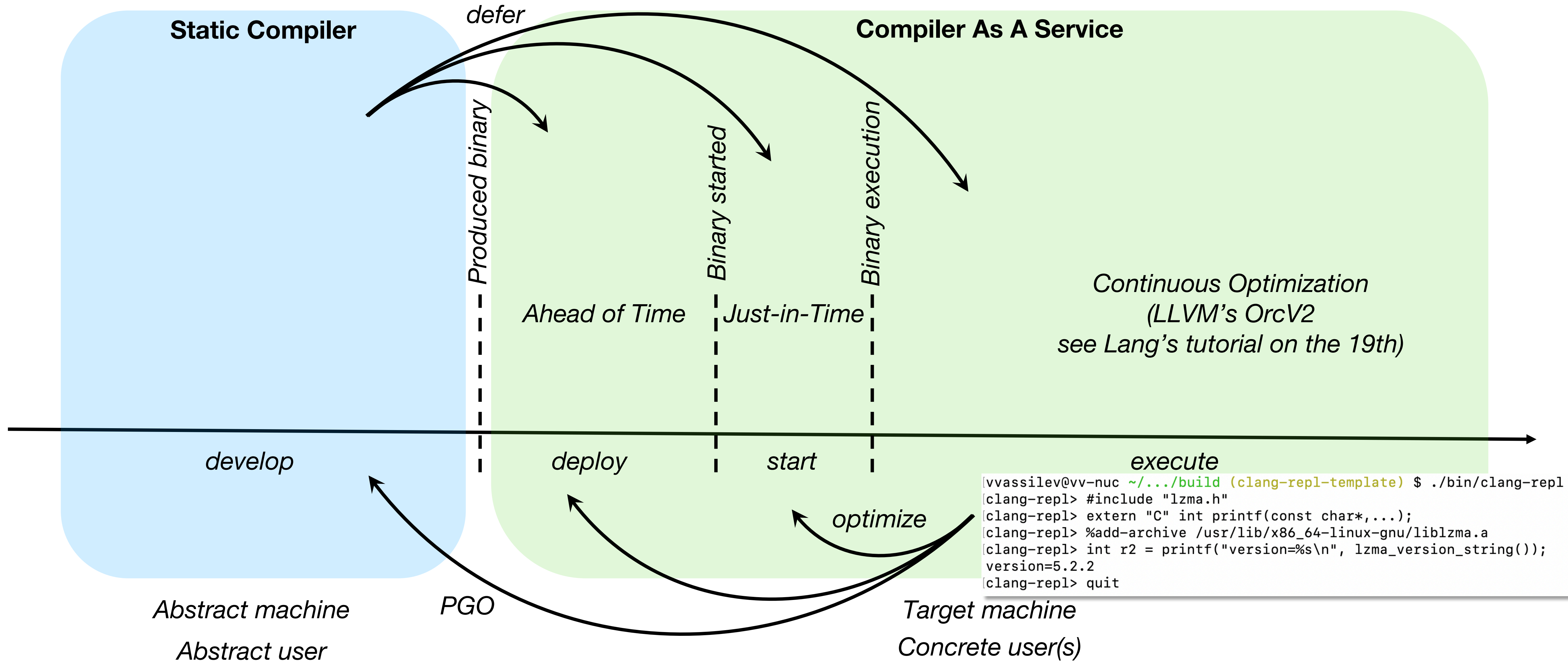
    # implicit template instantiation
    b.callme(a, 42)

```

```
[vassilev@vv-nuc ~/.../cpptemplate $ python3 template_instantiate_demo.py
callme in B!
callme in B!
vassilev@vv-nuc ~/.../cpptemplate $ █

```

Lifelong Optimization



Summary

- Interactive C++ is more than just a REPL
- CaaS allows to defer computations until runtime, possibly improving performance and reducing binary sizes (template instantiations)
- CaaS offers ways to extend the language for a particular use or domain

Thank You!

Selected References

- <https://blog.llvm.org/posts/2020-11-30-interactive-cpp-with-cling/>
- <https://blog.llvm.org/posts/2020-12-21-interactive-cpp-for-data-science/>
- <https://blog.llvm.org/posts/2021-03-25-cling-beyond-just-interpreting-cpp/>
- <https://Compiler-Research.org>
- <https://root.cern>

Q&A

Backup

ROOT – Scientific Data Analysis



- The ROOT data analysis package embeds Cling to enable interactive C++ but also to use it as a reflection information service for data serialization
- The ROOT and Cling technology are used to store around 1EB physics data facilitating more than 1000 scientific publications last 7 years
- The ROOT package is developed and maintained by the field of high-energy physics and organizations such as CERN, FNAL, GSI, University of Nebraska, UC San Diego, Princeton

Dynamic Scopes. Runtime Lookup

```
gCling->EvaluateT< /*ret type*/void>("ntuple->SetTitle()", /*context*/);
```

```
[root] ntuple->SetTitle()
```

```
error: use of undeclared identifier 'ntuple'
```

```
[root] TFile::Open("tutorials/hsimple.root"); ntuple->SetTitle()
```

```
(const char *) "Demo ntuple"
```

```
[root] gFile->ls();
```

```
TFile**      tutorials/hsimple.root      Demo ROOT file with histograms
```

```
TFile*      tutorials/hsimple.root      Demo ROOT file with histograms
```

```
OBJ: TH1F    hpx      This is the px distribution : 0 at: 0x7fadbb84e390
```

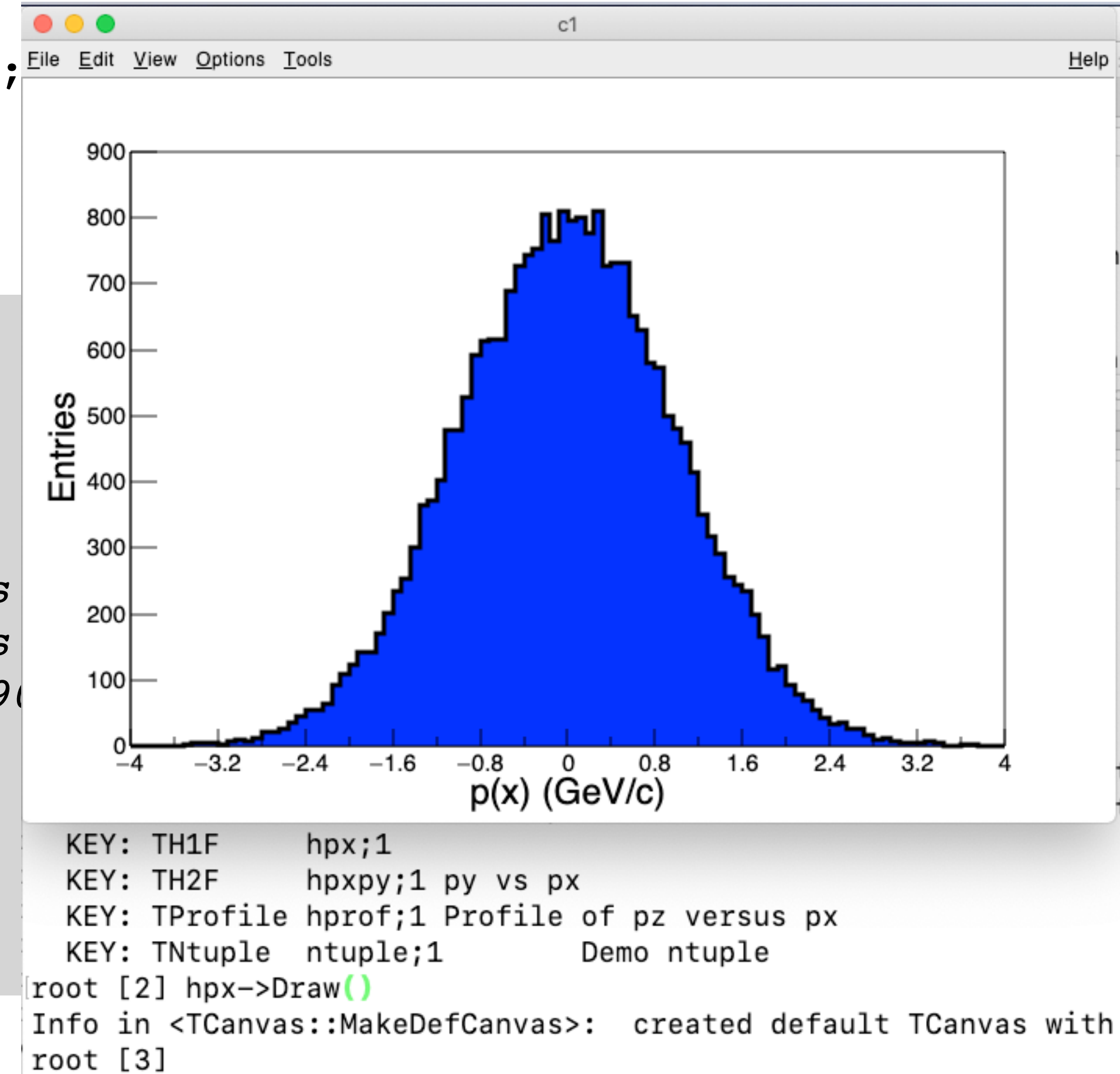
```
OBJ: TNtuple ntuple   Demo ntuple : 0 at: 0x7fadbb93a890
```

```
KEY: TH1F    hpx;1    This is the px distribution
```

```
[...]
```

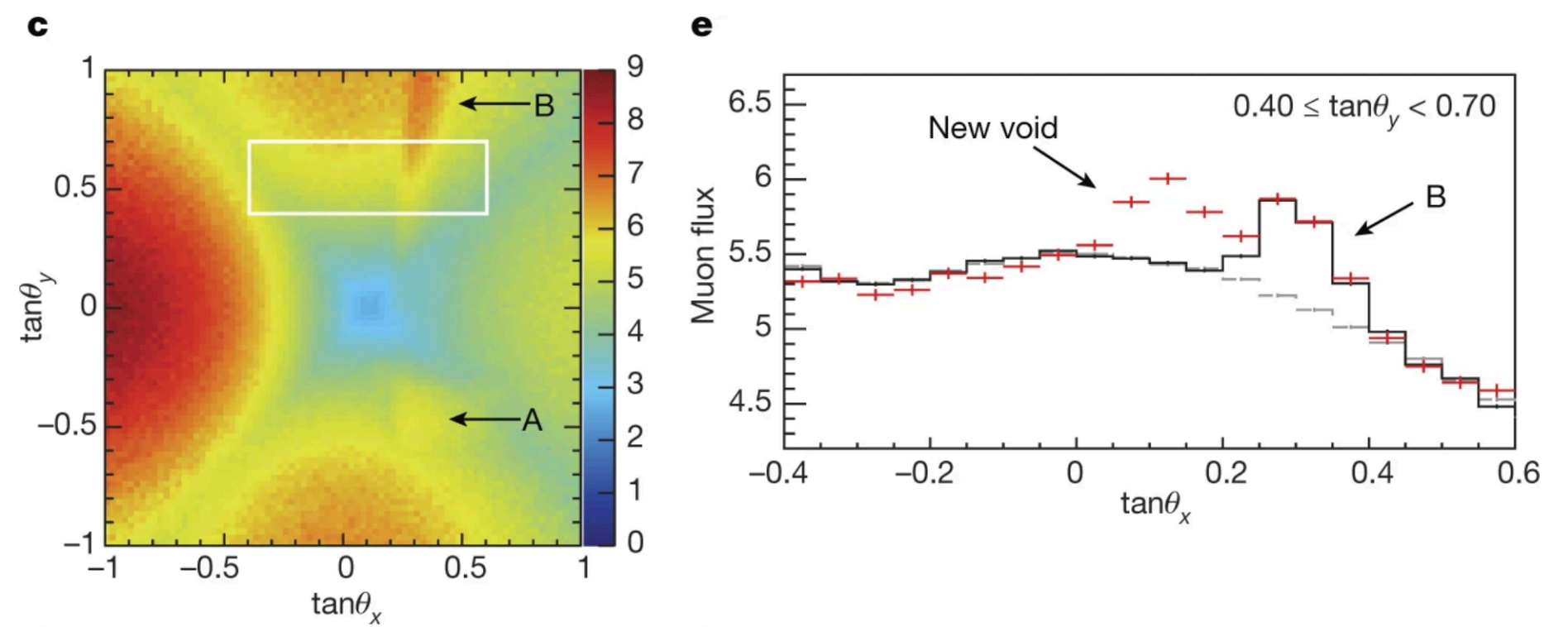
```
KEY: TNtuple ntuple;1 Demo ntuple
```

```
[root] hpx->Draw()
```

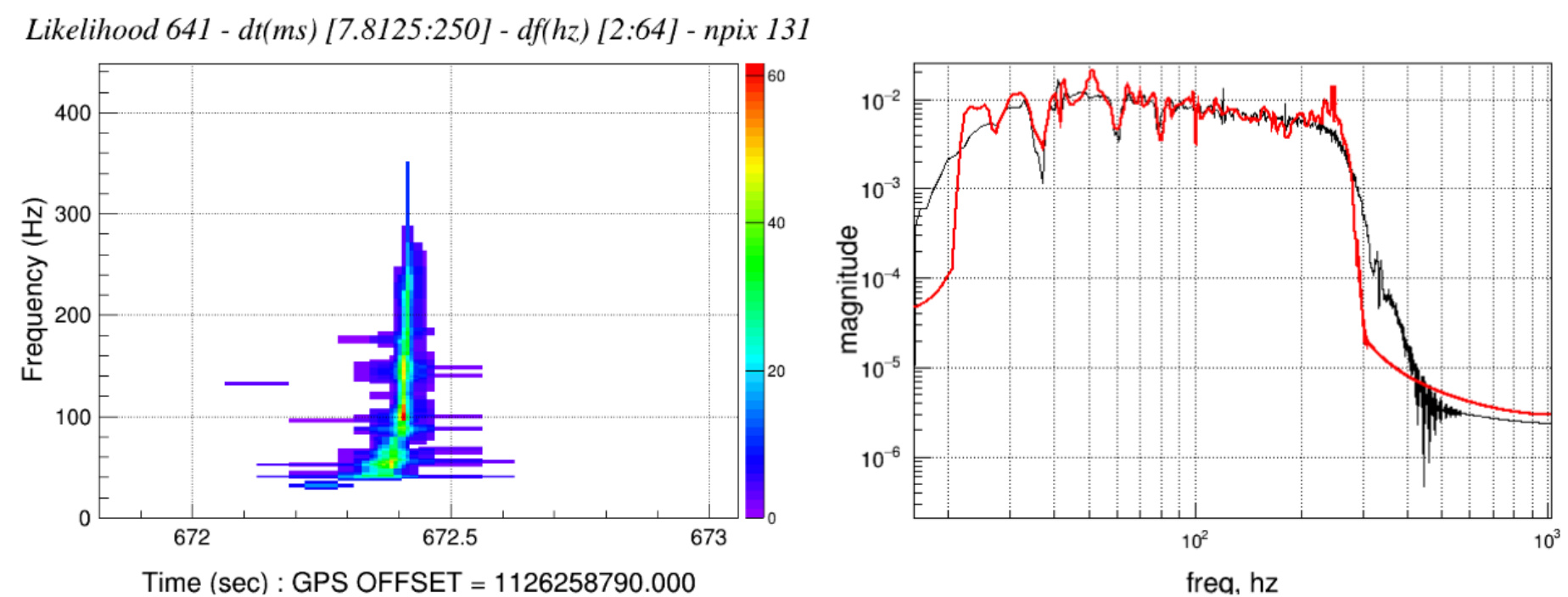


Eval-style programming enables Cling to be embedded in frameworks.

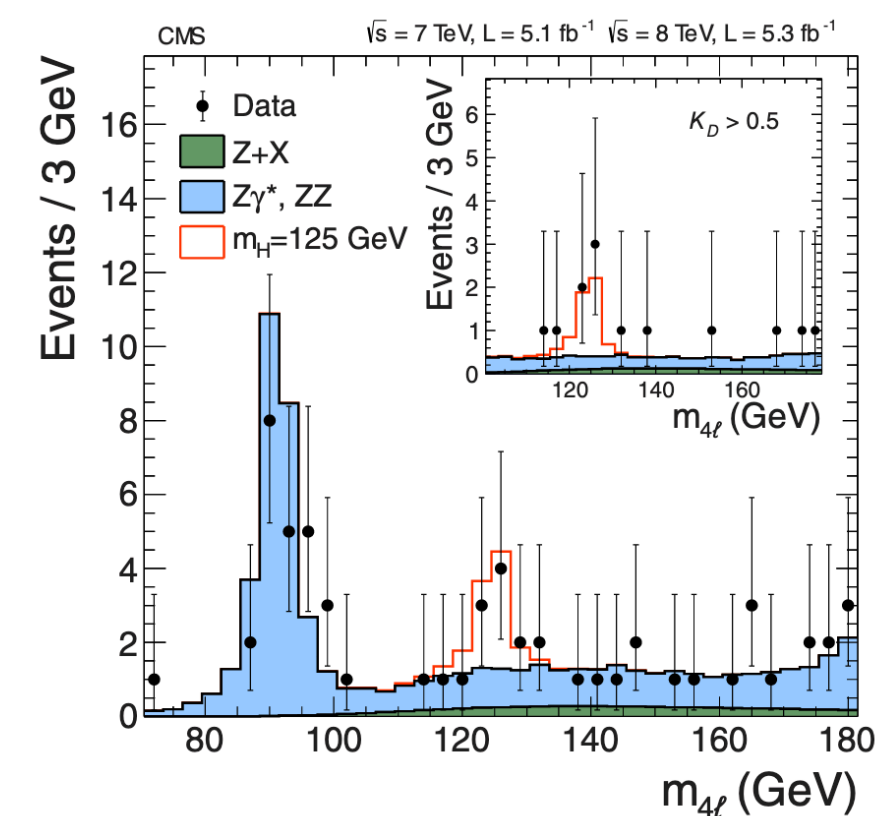
Impact of Interactive C++ in Physics



[1]



[2]



[3]

Scientific breakthroughs such as the discovery of the big void in the Khufu's Pyramid, the gravitational waves and the Higgs boson heavily rely on the ROOT software package

[1] K. Morishima et al, **Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons**, *Nature*, 2017

[2] Abbott et al, **Observation of gravitational waves from a binary black hole merger**. *Physical review letters*, 2016

[3] CMS Collab, **Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC**. *Physics Letters B*, 2012

Interpreting C++. Cling

- Cling was originally developed in the field of high energy physics to enable interactivity, dynamic interoperability and rapid prototyping capabilities to C++ developers.
- Cling supports the full C++ feature set including the use of templates, lambdas, and virtual inheritance.
- Cling adds a small set of extensions in C++ to allow interactive exploration and makes the language more welcoming for use.
- Cling compiles C++ code incrementally and relies on JIT compilation.
- Cling enables exploratory programming for C++.